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National threshold runoff estimation utilizing GIS in support of operational flash flood warning systems

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Abstract

Threshold runoff is the amount of excess rainfall accumulated during a given time period over a basin that is just enough to cause flooding at the outlet of the draining stream. Threshold runoff estimates are indicators of maximal sustainable surface runoff for a given catchment, and are thus an essential component of flash flood warning systems. Used in conjunction with soil moisture accounting models and areal rainfall data, they form the basis of the US National Weather Service (NWS) flash flood watch/warning program. As part of their modernization and enhancement effort, the NWS determined that improved flash flood guidance and thus improved threshold runoff estimation is needed across the United States, with spatial resolution commensurate to that afforded by the WSR-88D (NEXRAD) radars. In this work, Geographic Information Systems (GIS) and digital terrain elevation databases have been used to develop a national system for determining threshold runoff. Estimates of threshold runoff are presented for several locations in the United States, including large portions of the states of Iowa, Oklahoma, and California, and using several options in computing threshold runoff. Analysis of the results indicates the importance of channel geometry in flash flood applications. Larger threshold runoff estimates were computed in Oklahoma (average value of 34 mm) than in Iowa (14 mm) or California (9.5 mm). Comparisons of the threshold runoff estimates produced by the GIS procedure with those based on manually computed unit hydrographs for the selected catchments are shown as a preliminary measure of the accuracy of the procedure. Differences of up to about 15 mm for hourly rainfall durations were obtained for basins larger than 50 km^2.

Keywords: Hydrology; Flash floods; Forecasting; Distributed modeling; Geographic information systems; Radar

1. Introduction

Flooding is the worst weather-related hazard, causing loss of life and excessive damage to property. NOAA (1981) and NRC (1996) state that the average number of deaths due to flooding is 140 people annually, with nearly \$3.6 billion worth of property damaged or destroyed each year in US. In addition, it has been reported that flood damages are increasing at a rate of 5% per year (Barrett, 1983). The 1993 Mississippi Flood alone caused damages of more than \$15 billion and a loss of 38 lives (Galloway, 1994). Flood damage mitigation is provided through a variety of structural and non-structural methods. A significant non-structural method is the operation of flood warning systems. Continued improvements in flood warning systems are necessary to further mitigate flood damages and loss of life.

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In the United States, flash flood warnings are provided by the National Weather Service (NWS). A flash flood is defined as a flood which follows shortly (i.e. within a few hours) after a heavy or excessive rainfall event (Georgakakos, 1986; Sweeney, 1992). Flash flood warnings and watches are issued by local NWS Weather Forecast Offices (WFOs), based on the comparison of flash flood guidance (FFG) values with rainfall amounts. FFG refers generally to the volume of rain of a given duration necessary to cause minor flooding on small streams. Guidance values are determined by regional River Forecast Centers (RFCs) and provided to local WFOs for flood forecasting and the issuance of flash flood watches and warnings. The basis of FFG is the computation of threshold runoff values, or the amount of *effective* rainfall of a given duration that is necessary to cause minor flooding. Effective rainfall is the residual rainfall after losses due to infiltration, detention, and evaporation have been subtracted from the actual rainfall on the catchment level. It is the portion of rainfall that becomes surface runoff on the catchment scale. The relationship between FFG and threshold runoff is a function of the current soil moisture conditions, which are estimated in real time by operational soil moisture accounting models.

As part of its modernization efforts, the NWS identified several shortcomings with existing FFG procedures (Sweeney, 1992). Methods of determining threshold runoff estimates varied from one RFC to another, and in many cases, were not based on generally applicable, objective methods. Computed threshold runoff existed with coarse resolution. For example, there may have been only four distinct threshold runoff values within an RFC region (there are only 13 RFC regions that cover the US), while time duration of threshold runoff and flash flood guidance values varied among RFCs. These shortcomings lead to inconsistencies in FFG within and across RFC boundaries. To address these inconsistencies, the NWS outlined a plan to generate more accurate and consistent FFG, including a uniform and objective method of computing threshold runoff values (Fread, 1992), and a standard algorithm for determining FFG (Sweeney, 1992). It is noted that the determination of threshold runoff for a given effective rainfall duration is a one-time task. Determination of flash flood guidance is done frequently using current soil moisture conditions as estimated by operational hydrologic models.

The first step, and the focus of this paper, is the design and implementation of a consistent procedure for computing threshold runoff values. It is required that the method of threshold runoff computation be objective and based on sound hydrologic and hydraulic principles with known assumptions and limitations. The procedure must be applicable across the US, with implementation at regional RFCs. With the availability of high temporal and spatial resolution precipitation estimates accompanying the implementation of the national WSR-88D radar network, the enhanced procedure should also make use of the latest–available technology to produce estimates down to small scales. To support areal flash flood guidance, as opposed to basin-specific flash flood guidance, computed threshold runoff values are to be interpolated to a uniform grid corresponding to that of the WSR-88D radar rainfall observations (Hydrologic Rainfall Analysis Project, HRAP, grid). The developed procedure utilizes digital terrain databases, which are available nationally, and geographic information systems (GISs). This paper describes the methodology of threshold runoff computation, comparisons of threshold runoff values for different computation options and for different locations in the US, and comparisons of procedure-computed values with manually computed threshold runoff values.

2. Methodology

For the formulation of a method to compute threshold runoff nationally, the following requirements were identified:

- the method of threshold runoff determination must have a sound hydrologic/hydraulic basis;
- the method must be computationally efficient, given the national scale of computations required;
- digital terrain databases with national coverage and GIS should be utilized to facilitate the computations;
- estimates of any free parameters must be computable and stable over a region given the available national databases.

Threshold runoff has been defined as the amount of rainfall excess of a given duration necessary to cause flooding on small streams. Under the assumption that catchments respond linearly to rainfall excess, threshold runoff, R, may be found by equating the peak catchment runoff, determined from the catchment unit hydrograph of a given duration, to the stream flow at the basin outlet associated with flooding. Mathematically, this is expressed as:

$$Q_p = q_{pR}RA, \tag{1}$$

where Q_p is the flooding flow (cms of cfs), q_{pR} the unit hydrograph peak for a specific duration t_R, normalize d by catchment area (cms/km^2/cm or cfs/mi^2/in.), A the catchment area (km^2 or mi^2) and R the threshold runoff (cm or in.).

Rearranging, one can solve for threshold runoff:

$$R = Q_p/q_{pR}A \tag{2}$$

The solution is found by defining Q_p, q_{pR}, and A in such a way that they can be computed given the available data. The approach taken in this work has been to provide several options for threshold runoff determination suitable for varying data-availability scenarios. A description of these options follows.

2.1. The flooding flow, Q_p

This is perhaps the more difficult term to define. Flooding is generally associated with damaging conditions, which may be difficult to quantify in terms of flow over a region. One conservative measure of a "flooding flow" is the bankfull discharge. This definition of "flooding" is physically based, but is considered conservative as more than bankfull flow is generally needed to cause damage.

An alternative definition of the flooding flow is the flow of a certain return period. This definition is statistically based and carries the notions of risk and uncertainty associated with flooding. There is evidence of a good statistical relationship between the bankfull flow and a flow with a return period between 1 and 2 years (Henderson, 1966). This range of flows has been used as a surrogate for bankfull flow (e.g. Wolman and Leopold, 1957; Nixon, 1959; and also discussion in Riggs, 1990). In this application, the two-year return period flow is used as an alternative to bankfull flow as more than bankfull flow is necessary to produce flood damage. Each definition requires different sets of field data as described next.

The bankfull discharge is computed from channel geometry and roughness characteristics using Manning's steady, uniform flow resistance formula (Chow et al., 1988):

$$Q_p = Q_{\mathrm{bf}} = B_{\mathrm{b}}D_{\mathrm{b}}^{5/3}S_{\mathrm{c}}^{0.5}/n \tag{3}$$

where B_{b} is the channel top width at bankfull (m), D_{b} the hydraulic depth at bankfull (m), S_{c} the local channel slope (dimensionless), n the Manning's roughness coefficient and Q_{bf} the bankfull flow (cms).

This formulation makes the approximation of the wetted perimeter by the cross-sectional width (wide rectangular channel approximation).Georgakakos et al. (1991) based on data by Jarrett (1984), presents Manning's roughness coefficient (for $n > 0.035$) as a function of local channel slope, S_{c} (dimensionless), and hydraulic depth, D_{b} (m):

$$n = 0.43S_{\mathrm{c}}^{0.37}/D_{\mathrm{b}}^{0.15}. \tag{4}$$

Clearly, the computation of bankfull discharge requires channel cross-sectional data. Measurements of cross-sectional parameters result from limited local surveys and are not available nationally on a continuous spatial basis. Also, the available remotely sensed data with national coverage do not have the resolution needed to reliably estimate small-channel cross-sectional properties. Estimates of these parameters for unsurveyed streams must be made. This can be done using regional relationships between the cross-sectional parameters and other catchment and stream characteristics, such as catchment area or stream length, which may be determined through GIS and nationally available digital terrain data.

The two-year return period flow is the flow that is expected to be equaled or exceeded once every two years on average. To implement this option, the flooding flow is equated to the two-year return period flow:

$$Q_p = Q_2. \tag{5}$$

The two-year return period flow is based on extensive historical discharge records. The US Geological Survey maintains such streamflow records and has determined two-year return period flows with good national coverage. In general, though, such records are not available for all streams and all locations of

Table 1
Options for threshold runoff computation

	Flooding flow definition		Unit hydrograph options	
Options	Two-year return period flow, Q_2	Bankfull discharge Q_{bf}	Snyder's synthetic unit hydrograph	Geomorphologic unit hydrograph
Data required	Regional relationship for Q_2 (historic flow record)	Regional relationship for channel cross-sectional parameters (cross-sectional data)	Regional estimates of empirical coefficients	Regional relationship for channel cross-sectional parameters (cross-sectional data); regional estimates of R_L

interest. The two-year return period flow at ungauged locations may also be estimated using regional relationships with catchment, stream, and other characteristics such as annual precipitation (see USGS, 1994).

2.2. The unit hydrograph peak, q_{pR}

The catchment response is determined from the catchment unit hydrograph of a given duration. Two options are provided for unit hydrograph peak determination. As a first option, Snyder's empirical synthetic unit hydrograph was used to produce magnitude and time estimates for the unit hydrograph peak. The details of the formulation are reported in Carpenter and Georgakakos (1993), and are not included here as they are available in textbooks (e.g. Chow et al., 1988; Bras, 1990). The empirical coefficients of Snyder's formulation should be calibrated with field data for basins with similar drainage and storage capacity. This requires "observed" unit hydrographs for flash flood prone areas (i.e. unit hydrographs derived from observed stream flow and precipitation records). The NWS has determined "observed" unit hydrographs for some operational site-specific flow forecast locations, generally for larger basins. Few "observed" unit hydrographs exist for small to medium size streams and the values of the two empirical coefficients may be highly uncertain. Local data and knowledge must be used to estimate their values in the region of application.

The theory of the geomorphologic unit hydrograph (GUH) attempts to eliminate the uncertainty associated with the empirical coefficients of traditional synthetic unit hydrograph approaches. The catchment response is related to catchment and channel characteristics, which may be determined with GIS and digital terrain data. For these reasons, the GUH was selected as an alternative method in determining the unit hydrograph response.

Rodriguez-Iturbe and Valdes (1979) developed the geomorphologic instantaneous unit hydrograph based on the geomorphologic structure of basins, using Horton's geomorphologic laws (e.g. see Bras, 1990, for a description of Horton's laws). They began by expressing the peak magnitude and time to peak of the instantaneous unit hydrograph as a function of Horton's ratios, stream length and the catchment velocity. Rodiguez-Iturbe et al. (1982) eliminated the catchment velocity from the expressions and converted the peak magnitude and time to peak of the instantaneous unit hydrograph to the peak magnitude and time to peak of a unit hydrograph corresponding to a uniform rainfall excess of a given dura tion, t_R. Their results are reproduced here for easy reference:

$$Q_p = 2.42iAt_R/\Pi^{0.4}(1 - 0.218t_R/\Pi^{0.4}) \tag{6}$$

and

$$t_{pR} = 0.585\Pi^{0.4} + 0.75t_R \tag{7}$$

where

$$\Pi = L^{2.5}/(iAR_L\alpha^{1.5}), \tag{8}$$

$$\alpha = S_c^{0.5}/nB^{2/3} \tag{9}$$

where A is the drainage area (km^2), t_R the duration of effective rainfall (h), L the main stream length (km), i the effective rainfall intensity (cm/h), R_L the Horton's length ratio (dimensionless), S_c the local channel slope (dimensionless), n the Manning's roughness coefficient and B the top width (m).

Given that the threshold runoff, R, is equal to the rainfall intensity times its duration, $[it_R]$, Eq. (6) is reduced to:

$$Q_p = 2.42RA/\Pi^{0.4}(1 - 0.218t_R/\Pi^{0.4}) \tag{10}$$

To compute R, the value of Q_p, either Q_{bf} or Q_2, is substituted into the left hand side of (10) and α is computed at bankfull conditions (i.e. $B = B_b$). As with the bankfull flow, regional relationships are necessary to estimate the channel cross-sectional parameters involved in computing the GUH (B_b and S_c).

The data requirements for each of the options are summarized in Table 1. The combination of options yields four possible methods of computing the threshold runoff.

Method 1: Bankfull Flow (Q_{bf}) and Geomorphologic Unit Hydrograph (GUH).
Method 2: Bankfull Flow and Snyder's Unit Hydrograph.
Method 3: Two-Year Return Period Flow (Q_2) and Geomorphologic Unit Hydrograph.
Method 4: Two-Year Return Period Flow and Snyder's Unit Hydrograph.

2.3. Limitations

In each method, GIS is utilized to process digital terrain data and compute catchment-scale characteristics, such as drainage area, stream length and average channel slope. Regional relationships are needed to estimate channel cross-sectional and flow parameters from the catchment-scale characteristics for all locations within the region of application. The quality of the regional relationships, along with the assumptions of the theory, will indicate the applicability of various methods within certain regions or for certain events. For example, the assumption that the catchment responds linearly to rainfall excess, i.e. unit hydrograph theory is applicable, results in limitations on the size of the catchment. Small catchments are more non-linear than larger ones (Wang et al., 1981), especially during light and moderate rainfall (Caroni et al., 1986). High flows are more favorable to a linear assumption than low flows. The assumption of uniform rainfall excess over the catchment also implicitly limits the size of the catchment for which a unit hydrograph approach is reasonable. In many channels, the channel cross-section varies greatly over short distances, and may also change in time with the occurrence of floods. Therefore, bankfull discharge is difficult to determine in areas with unstable channel cross-sections. In some regions, the two-year return period flow significantly underestimates a flood flow, even bankfull flow. A longer-return-period flow may be more indicative of a flood flow, and if this is known a priori, may be implemented through the regional relationship for flow. Note, finally, the return period flow depends greatly on the length of the historical discharge record for streams in a region and on climate variability when climatic variables are included as predictors. The reliability of these values may vary from location to location. Knowledge of these limitations is vital in the selection of the method(s) to compute threshold runoff and in interpreting the threshold runoff estimates.

3. Implementation

The methodology described has been implemented in the software package, *threshR* (Kruger et al., 1993). Here, an overview of the system is described.

The procedure is run on a Hydrologic Unit basis (on the order of several 1000 km^2), with threshold runoff computations performed on subbasins down to approximately 5 km^2. Hydrologic Units are groups of stream networks and their associated drainage areas. They have been defined across the United States through the work of the US Water Resources Council, the US Soil Conservation Service and an Inter-Agency Committee on Water Resources (USGS, 1974, 1982). For a Hydrologic Unit of interest, four main steps of the procedure are performed:

1. Import and process digital terrain data into the GIS. Digital terrain data includes elevation, stream location and land use data.
2. Delineate streams and subbasins down to 5 km^2 in size and compute geometric properties of those subbasins.
3. Compute subbasin threshold runoff, based on method(s) selected and regional relationships.
4. Interpolate subbasin threshold runoff to grid-based threshold runoff, corresponding to the grid of the WSR-88D radars.

The Geographic Information System selected for this application was the public domain package GRASS, *version 4.0*. GRASS (Geographic Resources Analysis Support System) was developed at the US Army Construction Engineering Research Laboratory (USACERL, 1983). In addition to the capabilities to import and display data from a variety of sources, GRASS includes a subroutine, *r.watershed*, which delineates streams and catchments based on digital elevation data. *r.watershed* determines the stream drainage network based on the A^T, or least cost, search algorithm and mimics the work of an experienced cartographer in delineating hydrologic divides (Ehlschlaeger, 1990). The digital elevation data utilized in the program is the Defense Mapping Agency (DMA) 1:250,000-scale digital elevation model. This data has a 90 m resolution and it is available nationally from the USGS (http://edcwww.-cr.usgs.gov/doc/edchome/ndcdb/ndcdb). Based on the initial sensitivity studies in flat areas, the elevation data is artificially lowered, or "carved", at the location of lakes, streams, and reservoirs to improve the *r.watershed* delineation of the streams and basins. EPA river reach files provide digital stream locations based on digitization of 1:100,000-scale topographic maps. The location of lakes and reservoirs, along with the Hydrologic Units boundary, are derived from 200 m resolution, 1:250,000-scale USGS Land Use/Land Cover Composite Thematic Grid files.

The accuracy of the *r.watershed* delineation of watersheds and streams was examined in Carpenter and Georgakakos (1993) and Sperfslage et al. (1994) for the mild sloping areas of Iowa and Oklahoma. Their estimates may be considered conservative for areas of strong topographic relief. This analysis showed only a 3% error in area when comparing the GIS-determined Hydrologic Unit areas with the area of the Units as defined by the USGS. To assess the sub-catchment delineation accuracy, basins with areas in the range (2–80 km^2) were manually delineated from 1:24,000-scale topographic maps, and compared to the GIS-computed sub-catchment areas. A total of 15 basins were delineated in Oklahoma and 17 in Iowa. When comparing areas without the use of stream carving, differences were in the range (−13 to +29%) in Oklahoma, with an average of +5.6%, and (−43 to +11%) in Iowa, with an average of −7.9%. In both regions, smaller sub-catchments yield generally higher errors in delineation. The delineation of streams was examined by the computed length and by physical location for a limited sample of eight streams in Oklahoma. The errors in stream length ranged from −7 to +32% with an average of +16%. The location of the GIS-computed streams was compared to that of the EPA river reach streams on a cell-by-cell (90 m on a side) basis. The percentage of "matched" cells (both the GIS and EPA identified the cell as "a stream") for the eight streams ranged from 36 to 76%, with an average of 55%. In cases of a miss, the average distance between the EPA stream and the GIS stream was about 300 m. There was significant improvement in delineating streams when the location of streams, lakes and reservoirs are "carved" into the elevation data prior to *r.watershed* processing.

A higher resolution (30 m) digital elevation database is available from the USGS in the 1:24,000-scale Digital Elevation Model (DEM) database. In a test case in Ohio, the improvement in stream delineation when using the 30 m data is comparable to the improvements observed when the location of the streams are "carved" into the DMA elevation data as shown in Iowa and Oklahoma. Although, the DEM data shows significant improvement in stream delineation and is desirable for use in operational threshold runoff estimation, this database lacks national coverage. Therefore, the development of the procedure and software package continued with the DMA (90 m) database.

r.watershed output includes basin network or connectivity information, subbasin areas, lengths and slopes for both individual subbasins and accumulated along the stream network. This information, along with the parameters of the regional regression relationships, is used to compute threshold runoff. Depending on the method specified, a varying set of regression parameters is read. In addition to options in the method of computing threshold runoff, the procedure allows flexibility in defining the time of effective rainfall, t_R, to obtain estimates of threshold runoff for various storm durations. Due to limitations in unit hydrograph theory, threshold runoff values for sub-catchments with accumulated drainage areas greater than 2000 km^2 are not computed.

Finally, the subbasin threshold runoff values are interpolated to a spatial grid. The grid is a user-specified multiple of the HRAP grid, corresponding to the

Table 2
Application regions

	California	Iowa	Oklahoma
No. of hydrologic units processed	11	31	38
Total area (km^2) of hydrologic units	16,540	110,990	154,740
Range in HU area (km^2)	88–3805	1810–6370	1790–8260
Methods of computation	One	All four	All four
Duration of effective rainfall (h)	1	1	1, 3, and 6

WSR-88D weather radar. Each grid node is assigned the subbasin threshold runoff value of the subbasin containing the node. If a node falls within a subbasin with a zero threshold runoff value, its value is computed from surrounding subbasins based on an inverse-distance weighting. The gridded threshold runoff values are produced to support gridded flash flood guidance used with radar precipitation estimates.

The *r.watershed* procedure to delineate sub-catchments is, by far, the most computationally intensive part of the procedure. For example, it took approximately 100 min of CPU time to process an area of about 5000 km^2 on an HP/UX 9000 series workstation. The time required for *r.watershed* processing increases substantially as the size of the analysis area, a computational region defined as a box around the Hydrologic Unit, increases. In an effort to decrease computational time, differences in *r.watershed* processing times were examined for different resolutions and for different computing platforms. As higher resolution increases the amount of data to be processed for a given analysis area, longer processing times are expected for higher resolutions. In fact, for the area in Ohio, processing time for the 30 m resolution data was nine times longer than the same area with 90 m resolution data on an HP/UX system. The sensitivity of the computed threshold runoff to data resolution was examined. For several areas, the watershed delineation was performed at a resolution of 540 m instead of 90 m (one in every six data points were used). Threshold runoff was then computed using the geometric properties of both the 540 and 90 m watershed runs. Processing at this coarse resolution substantially decreased the computational processing time for *r.watershed*. However, upon examination of the computed threshold runoff values, non-negligible degradation in the distribution of the values was observed for the 540 m runs.

Finally, a number of CPU run-time inter-comparisons were made for various computational platforms (i.e. CRAY, HP 9000, PC/Linux). The results on PCs running under Linux were very encouraging and outperformed all other cases. The performance of the computers was judged by the ratio of *r.watershed* execution times. In limited testing (two Hydrologic Units in California and one in Oklahoma) this performance ratio for PC/Linux: HP9000: Cray4 was 1:2:5. Processing on a CRAY offered no real advantages given the present *r.watershed* software (Sperfslage and Georgakakos, 1998).

4. Application

Threshold runoff has been computed for several large regions in the US. This includes essentially the states of Iowa and Oklahoma, and large areas in California. A summary of the particulars of the applications in each of these regions is provided in Table 2. The procedure has been applied to 80 Hydrologic Units, totaling more than 282,000 km^2. Within these regions, various methods and effective rainfall durations were used. In this section, the application and results of the threshold runoff procedure are described.

The first step in implementing the procedure is to develop regional relationships to estimate channel cross-sectional parameters and two-year return period flows at each of the sub-catchments delineated by the *r.watershed* routine. In some cases, such relationships may already be established (e.g. Tortorelli and Bergman, 1985; Leopold, 1994). For regions without established relationships, the data must be available to

Table 3
Regional relationships for flow and cross-sectional parameters

Parameter	California	Iowa	Oklahoma
Q_2	–	$Q_2 = 20.40A^{0.0607}S^{0.440}$, $R = 85\%$	$Q_2 = 0.03A^{0.59}P^{1.84}$ (Tortorelli and Bergman, 1985)
B_b	$B_b = 3.29A^{0.3714}$ (Leopold, 1994)	$B_b = 2.80A^{0.363}$, $R = 91\%$	$B_b = 2.33A^{0.542}$, $R = 82\%$
D_b	$D_b = 0.3A^{0.261}$ (Leopold, 1994)	$D_b = 0.82A^{0.160}$, $R = 50\%$	$D_b = 1.03A^{0.198}$, $R = 40\%$
S_c	$S_c = 0.006A^{-0.385}$	$S_c = 0.045A^{-0.203}S^{0.564}$, $R = 65\%$	$S_c = 0.006A^{-0.385}$, $R = 66\%$

develop such relationships. In Iowa and Oklahoma, sets of channel cross-sectional data were available and utilized to develop these regional relationships.

4.1. Regional regression relationships

The Iowa City, Iowa Office of the USGS provided surveyed data for approximately 75 locations in Iowa on distinct streams near stream gauging stations (Eash, 1991). The dataset included estimates of bankfull width, hydraulic depth, and local slope, along with a description of potential measurement errors. The discussion of measurement error was used to identify 43 locations with "well-defined" estimates. The two-year return period flow at the local stream gauge was added to the database. A power-law relationship with the predictor variables of drainage area, A (km^2), stream length, L (m), and average channel slope, S (dimensionless) was explored:

$$X = \alpha A^{\beta} L^{\gamma} S^{\delta} \quad (11)$$

where X represents any of: bankfull top width (B_b in m), hydraulic depth (D_b in m), local channel slope (S_c), and two-year return period flow (Q_2 in cms). At each of the 43 locations, catchment area, A, was given by the USGS stream gauge description. Stream length and average channel slope were manually determined using 1:250,000-scale topographic maps. A statistical software package (Minitab Inc, 1989) was used to evaluate all possible relationships for varying subsets of predictor variables. Carpenter and Georgakakos (1993) provide a detailed discussion of the statistical measures used to evaluate the relationships. The selected relationships and their correlation coefficients are given in Table 3. For Iowa, the two-year flow and top width relationships have fairly strong correlation coefficients of 85 and 91%, respectively. The hydraulic depth and local channel slope regressions show significantly weaker correlation values of 50 and 65%, respectively.

A similar dataset was developed for the state of Oklahoma with the assistance of the Oklahoma City Office of the USGS. This office provided discharge measurements (depth–velocity) and area–slope data reports, which were used to derive estimates of bankfull widths, hydraulic depth and local channel slope. Estimates for 13 streams were derived and used in establishing the regional relationships. In addition to the predictors of drainage area, stream length and slope, the average annual precipitation was also used. Again at each location, the area was given by the USGS stream gauge description, and stream length and channel slope were manually determined using 1:250,000-scale topographic maps. A table of average annual precipitation (cm) was digitized based on data provided in Tortorelli and Bergman (1985). A power-law type relationship of the form:

$$X = \alpha A^{\beta} L^{\gamma} S^{\delta} P^{\rho} \quad (12)$$

was fit to the data with X representing B_b, D_b, or S_c. Similar analysis as with the Iowa data was performed using the Minitab software (Carpenter and Georgakakos, 1995). In Oklahoma, the top width regression has the highest correlation coefficient of 82%. For local channel slope, the correlation coefficient is 66% and for hydraulic depth, it is 40%. In both Iowa and Oklahoma, the relationship of top width with drainage area shows the highest correlation, followed by local slope and then hydraulic depth.

Leopold (1994) provides relationships for top width and hydraulic depth as a function of drainage area based on stream data in the San Francisco, California area. These relationships were utilized for the computations in California. No information was available on local channel slope in California. The relationship

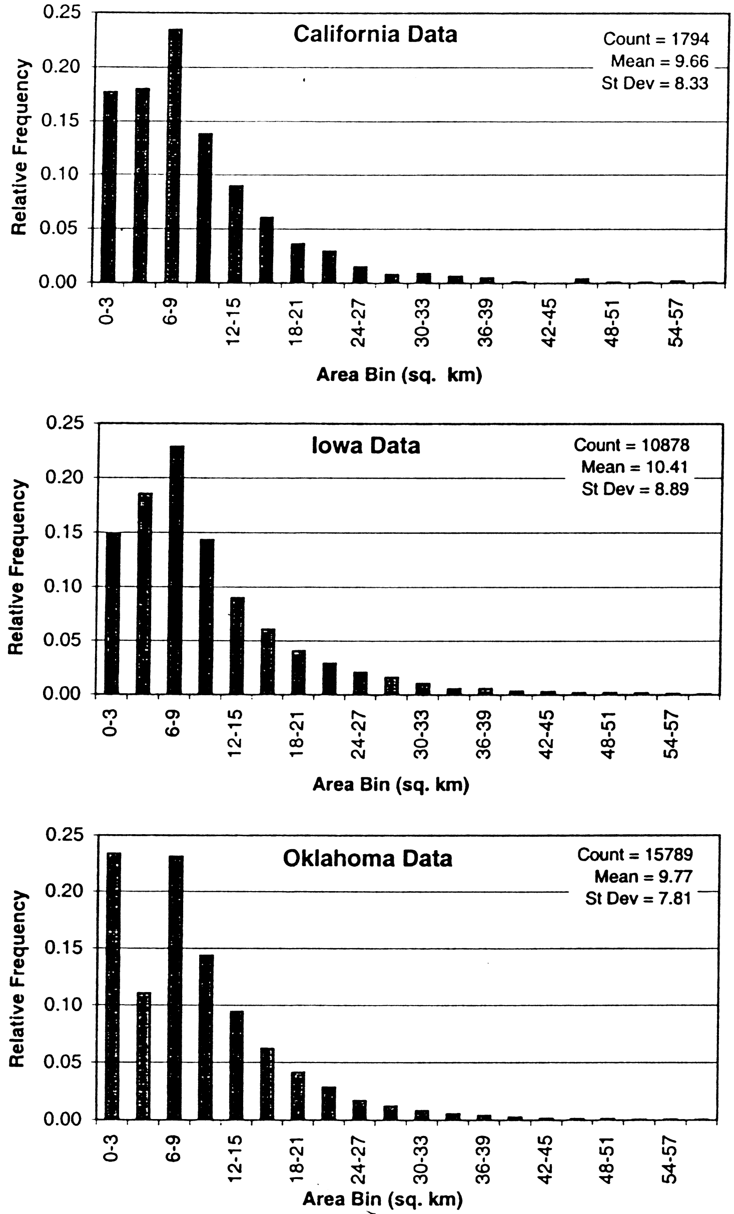


Fig. 1. Relative frequencies of subbasin drainage area.

between local channel slope and drainage area developed in semi-arid Oklahoma was used.

4.2. *Threshold runoff results*

With the regional relationships established, the procedure to compute threshold runoff can be applied. In this section, results of the application in Iowa, Oklahoma and California are discussed. The results are discussed in terms of (a) the characteristics of the watershed geometric parameters as computed through the GIS, (b) the characteristics of the unit hydrograph methods, and (c) the threshold runoff values.

The output of the GIS-computed catchment geome-

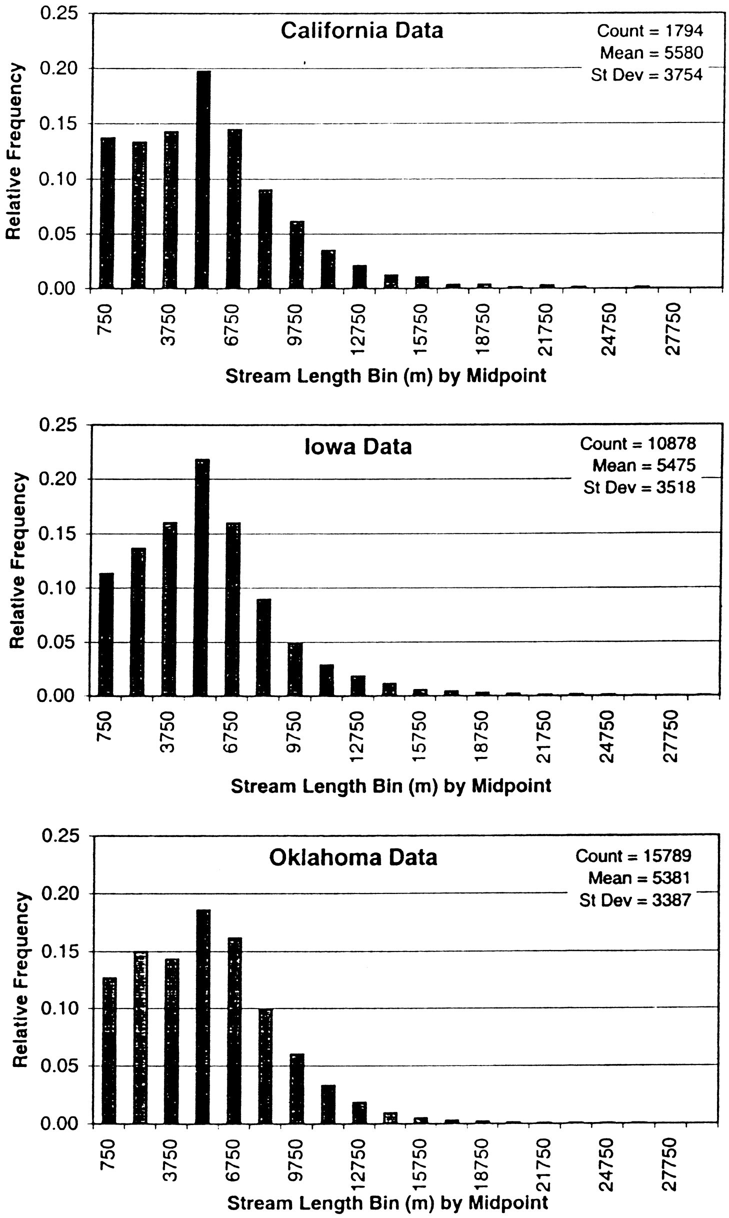


Fig. 2. Relative frequencies of subbasin stream length.

try (*r.watershed* output) includes drainage area, channel average slope, and stream length for (a) individual subbasins and (b) accumulated along the stream network. Figs. 1–3 show the relative frequency distributions for the individual subbasin parameters (area, length and slope) for the three regions. A greater number of Hydrologic Units were processed in Iowa and Oklahoma than in California, so the frequency is normalized by the number of subbasins in each region. The distributions are strikingly similar in shape for the three regions, with some variation for the lower values of drainage area (0–12 km^2), stream length (0–6000 m), and in the distributions of slope. Note that all distributions display an exponential

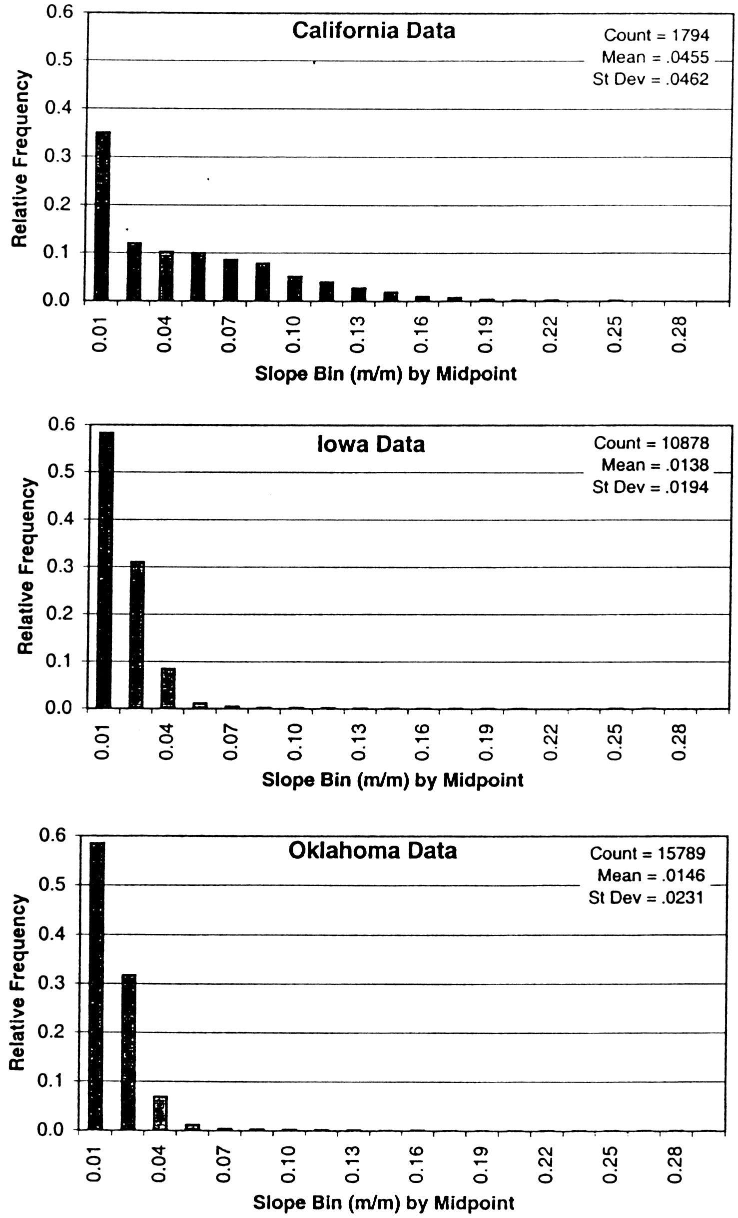


Fig. 3. Relative frequencies of subbasin slope.

decay in values, with far fewer large values of subbasin area, length, and slope than small values. The average values of subbasin area and stream length are very close in value for the three regions. The average subbasin size is near 10 km^2, and the average stream length is about 5500 m. However, the average subbasin slope is almost four times larger in California (0.046 m/m) than in Oklahoma or Iowa (both nearly 0.014 m/m). Statistics of the accumulated basin characteristics are shown in Table 4. In addition to the greater number of Hydrologic Units processed in Oklahoma and Iowa (see Table 2), this table shows that this included Hydrologic Units larger in size. The range of accumulated area and of stream length are

Table 4
Geometric characteristics for three application regions

	California	Iowa	Oklahoma
Number of subbasins	1794	10,878	15,879
Cumulative area (km^2)			
Range	5–3680	5–11,690	5–19,514
Average	215	325	566
Cumulative slope			
Range	0–0.2428	0–0.0644	0–0.0802
Average	0.0544	0.0147	0.0145
Cumulative length (m)			
Range	2463–178,210	2090–252,390	2475–434,910
Average	24,250	29,250	34,910

larger in these regions, as are the average values. As with the subbasin slope, the average accumulated slope is larger in California (0.05 m/m) than the flatter Central Plains Regions (0.015 m/m). Overall, the similarity among the distributions of subbasin area and channel length of the three regions is remarkable given their very different physiographic and climatic regimes.

In computing threshold runoff, the procedure computes and stores the unit hydrograph peak and time to peak. In the geomorphologic unit hydrograph, which depends only on topographic data, a linear approximation of the unit hydrograph peak is made and the time to peak is computed from Eq. (7). Relative frequency histograms for these parameters are shown in Figs. 4 and 5. Again, the frequency is normalized by the number of subbasins for which threshold runoff is computed. Average values of the unit hydrograph peak increase from 0.15/h in California and Oklahoma to 0.18/h in Iowa. Also, the distribution of the unit hydrograph peak exhibits bimodal properties in California and Iowa. The shapes of the distributions for the time to peak are very similar among the three regions. Average time-to-peak values do vary slightly among the regions: California, 5.6 h; Iowa, 5.2 h; Oklahoma, 6.2 h.

The distribution of magnitude and time of the unit hydrograph peak with the drainage area is illustrated in Fig. 6 for Oklahoma and for the geormorphologic unit hydrograph with a 1 h effective rainfall duration. Values are plotted for source basins only. Source basins were defined in the procedure as basins with drainage areas less than 35 km^2 which contain the source of a stream. These are catchments particularly prone to flash flooding. The unit hydrograph peak magnitude shows a decreasing trend with increasing drainage area. For the example shown, the average peak is approximately 0.28/h at 5 km^2 and decreases to 0.14/h at 35 km^2. The variability of the peak also decreases as the drainage area increases. The time to peak tends to increase as drainage area increases. The variability in the time to peak appears less dependent on drainage area, up to approximately 25 km^2. The decrease in variability at larger drainage areas may be due in part to sampling effects with fewer data points at these larger areas. Similar trends are observed for the other methods and regions.

Turning to the computed threshold runoff estimates, Fig. 7 displays the relative frequency of threshold runoff of hourly duration for the three regions and for Method 1 (Q_{bf}/GUH). Significant differences are apparent. Nearly all of the values in California fall below 16 mm (approximately 96%). In fact, more than 80% of the computed values fall in the 8–12 mm range. In Iowa, approximately 95% of the threshold runoff values are less than 20 mm. However, in Oklahoma, nearly all values are greater than this level. The values in Iowa and Oklahoma are larger and have a wider range than in California. Average threshold runoff values are 9.5 mm in California, 14 mm in Iowa, and 34 mm in Oklahoma. The range of values in California is 5–22 mm, whereas the range in Iowa is 6–30 and 17–72 mm in Oklahoma. Given the similar distributions of catchment geometry data in all three regions (i.e. subbasin area and stream length), these results are believed to be a reflection of the channel morphology (e.g. channel width and

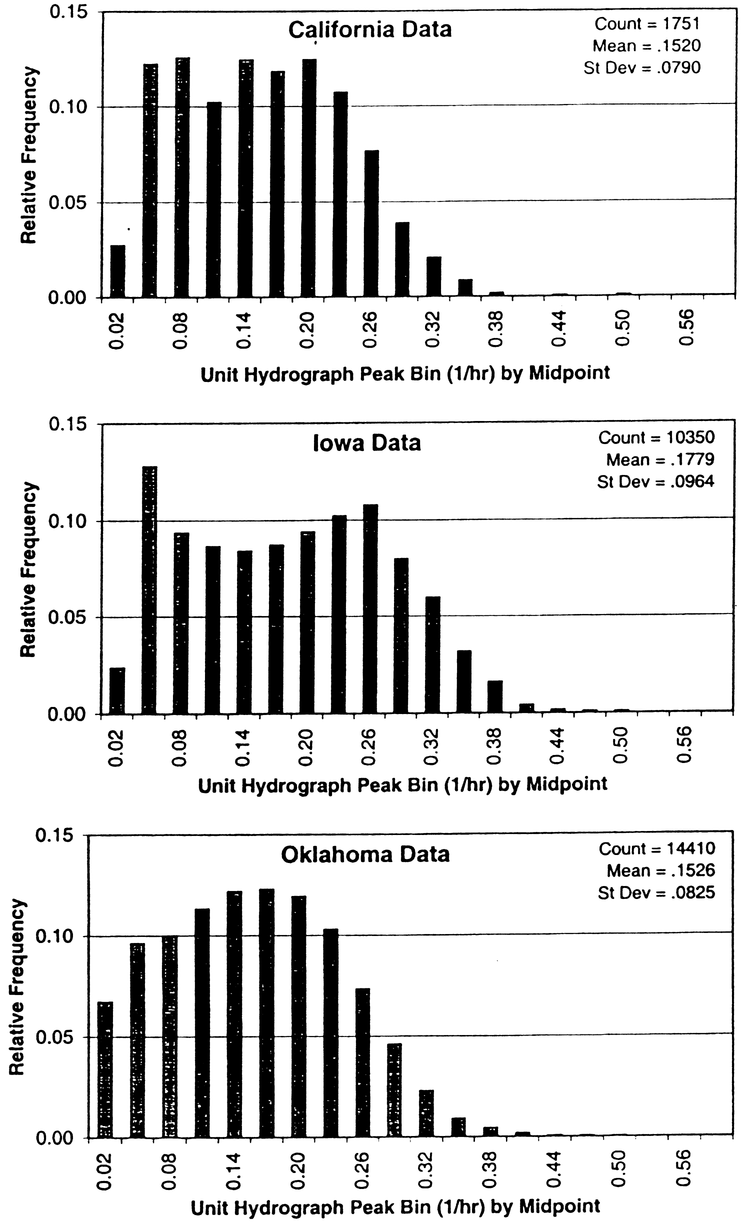


Fig. 4. Relative frequencies of unit hydrograph peak for geomorphologic unit hydrograph method.

depth), which in turn is a reflection of the action of climate on terrain.

To illustrate the differences among computational methods, Fig. 8 shows the relative frequency histograms of 1 h threshold runoff for each of the four methods for Oklahoma. The shapes of the distributions are more similar between Methods 1 and 2 (Q_{bf}) and between Methods 3 and 4 (Q_2) than between Methods 1 and 3 (GUH) or Methods 2 and 4 (Snyder's). This may indicate that the computed threshold runoff is more sensitive to the definition of the flooding flow than the unit hydrograph method. The distributions for Methods 3 and 4 are shifted to the left (to lower threshold runoff values) when

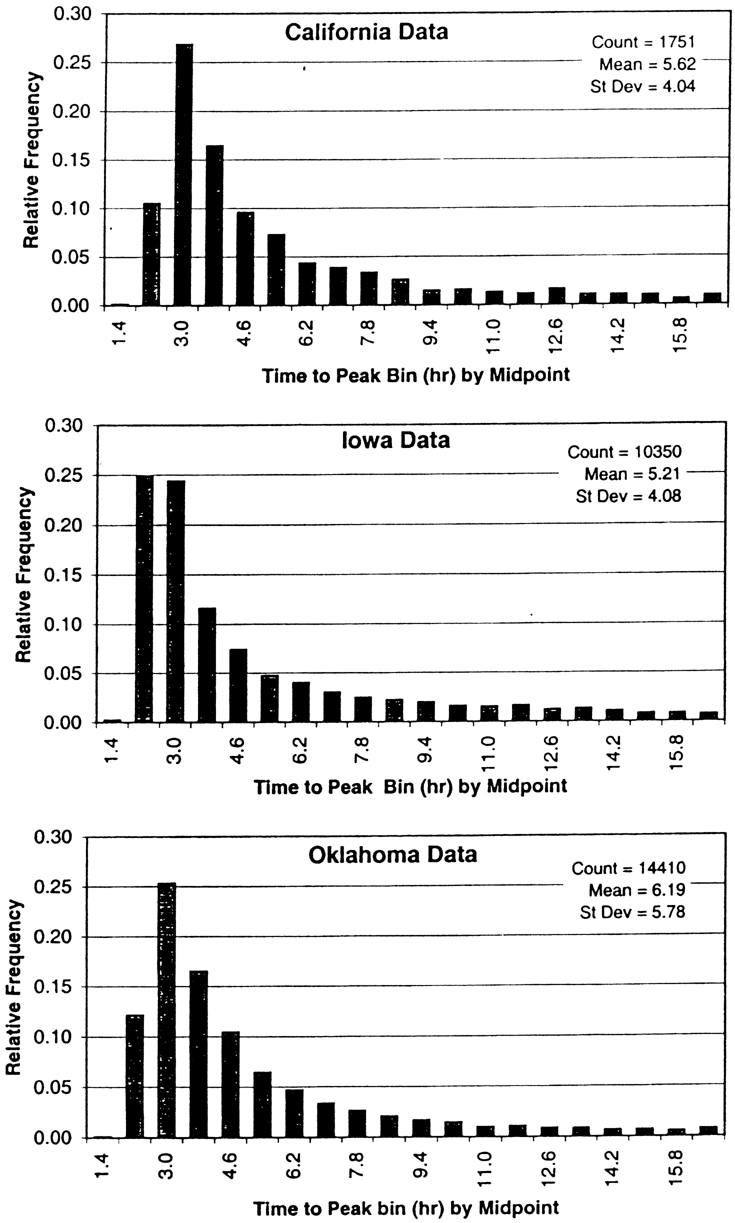


Fig. 5. Relative frequencies of time to peak for geomorphologic unit hydrograph method.

compared to the distributions for Methods 1 and 2. This implies that the bankfull flow methods yield higher threshold runoff than the two-year return period flow methods, and thus that the computed bankfull flows are higher than the computed two-year return period flows in Oklahoma.

In Iowa, the distributions (not shown herein) are more similar among the methods. The similarity in distribution shape between Methods 1 and 2 and between Methods 3 and 4 exists. However, there is no shift in the distributions as a function of the flooding flow, indicating that the two-year return period flow is a reasonably good estimate of bankfull flow there.

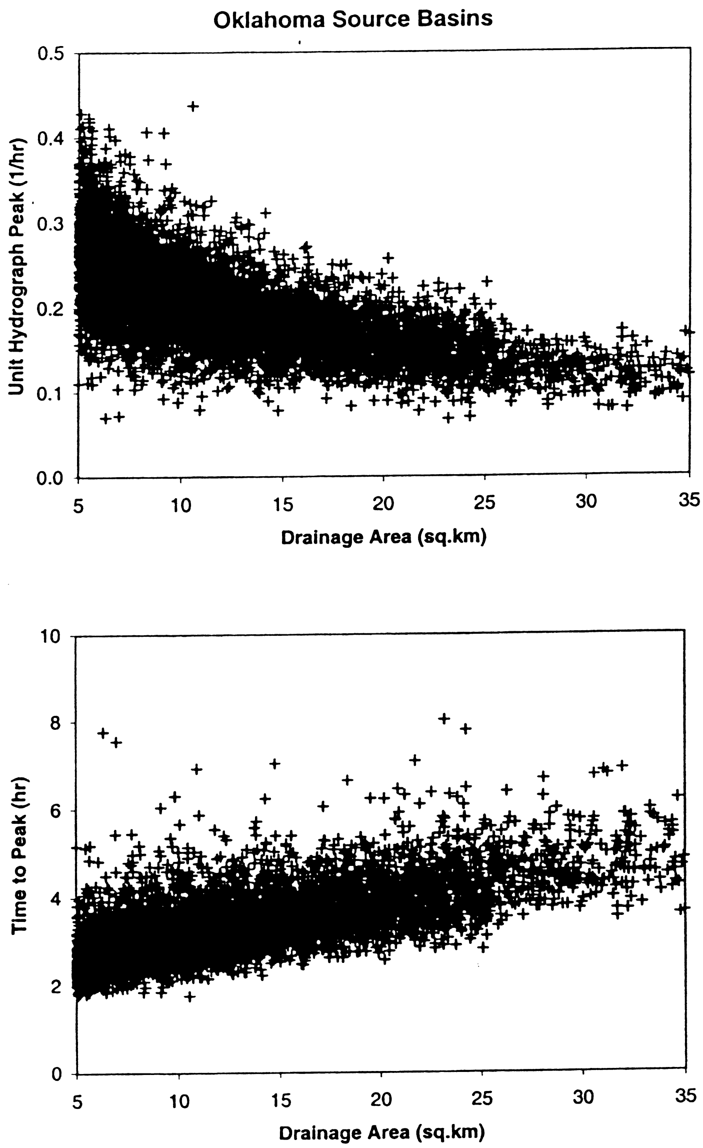


Fig. 6. Distribution of: (a) the unit hydrograph peak; and (b) time to peak for Oklahoma source basins (drainage area between 5 and 35 km^2).

Fig. 9 illustrates the effect of increasing the effective rainfall duration, t_R. For each method, this figure shows the relative frequency histograms for the 1-, 3-, and 6-h runs in Oklahoma. Clearly, there is a shift to higher threshold runoff as the effective rainfall duration increases. This effect is most pronounced in Method 1. To judge the relative magnitude of the shift in distributions, the difference between the 1 h mean threshold runoff value and the 6 h mean value was computed for each of the four methods. The differences were 30.3, 14.9, 21.4, and 8.5 mm for Methods 1, 2, 3, and 4, respectively. The higher differences in Methods 1 and 3 indicate greater sensitivity to the effective rainfall duration for the geomorphologic unit hydrograph method.

In Fig. 10, the threshold runoff values for 3- and 6-h effective rainfall duration are plotted against the corresponding threshold runoff values for an 1 h effec-

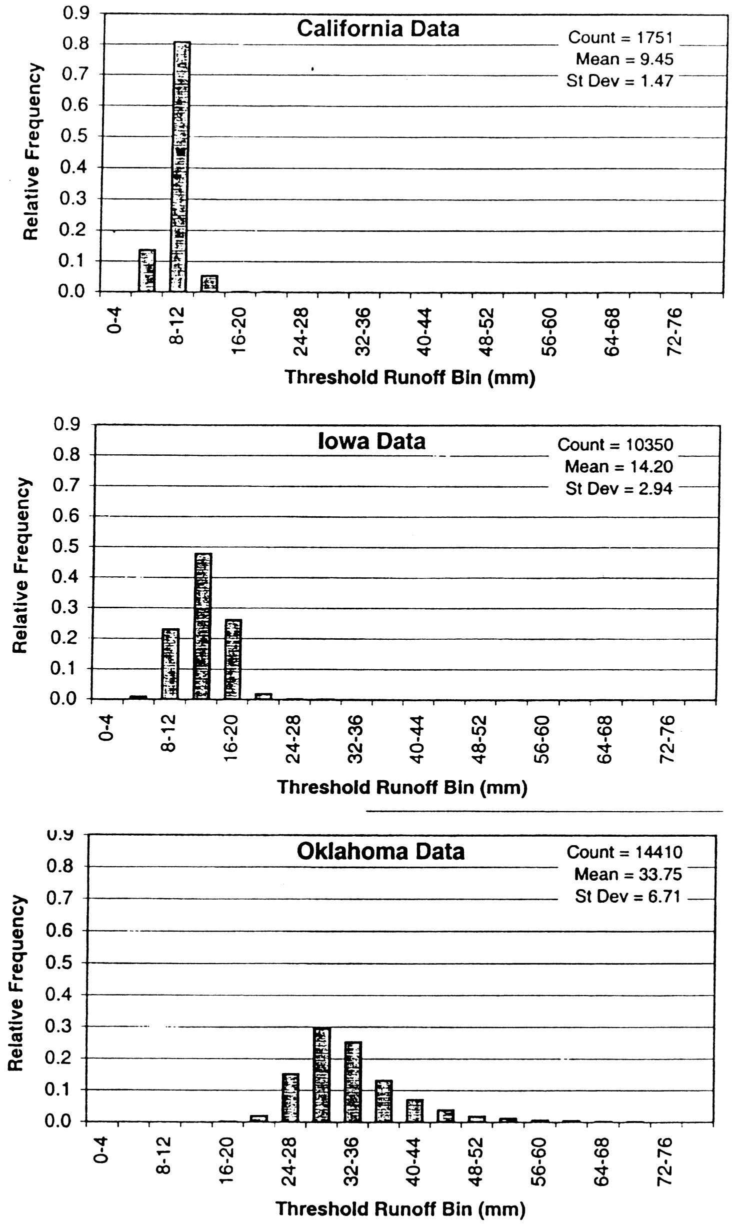


Fig. 7. Relative frequencies of hourly threshold runoff for method 1.

tive rainfall duration. This comparison is shown for source basins only (drainage areas less than 35 km^2) and for threshold runoff up to 76 mm (3 in.). Again, the increase in threshold runoff with effective rainfall duration is apparent. Fig. 10 may be used to estimate threshold runoff for durations of 3 and 6 h from the 1 h duration. It is clear from the greater scatter for the 6 h duration that such estimation will yield reliable results only for the duration of 3 h.

In the geomorphologic unit hydrograph methods, the above results utilized a constant value of Horton's length ratio, R_L (see Eq. (8)). In the preliminary work, a regional value of 1.9 was established using data from Oklahoma. This value of 1.9 was applied for

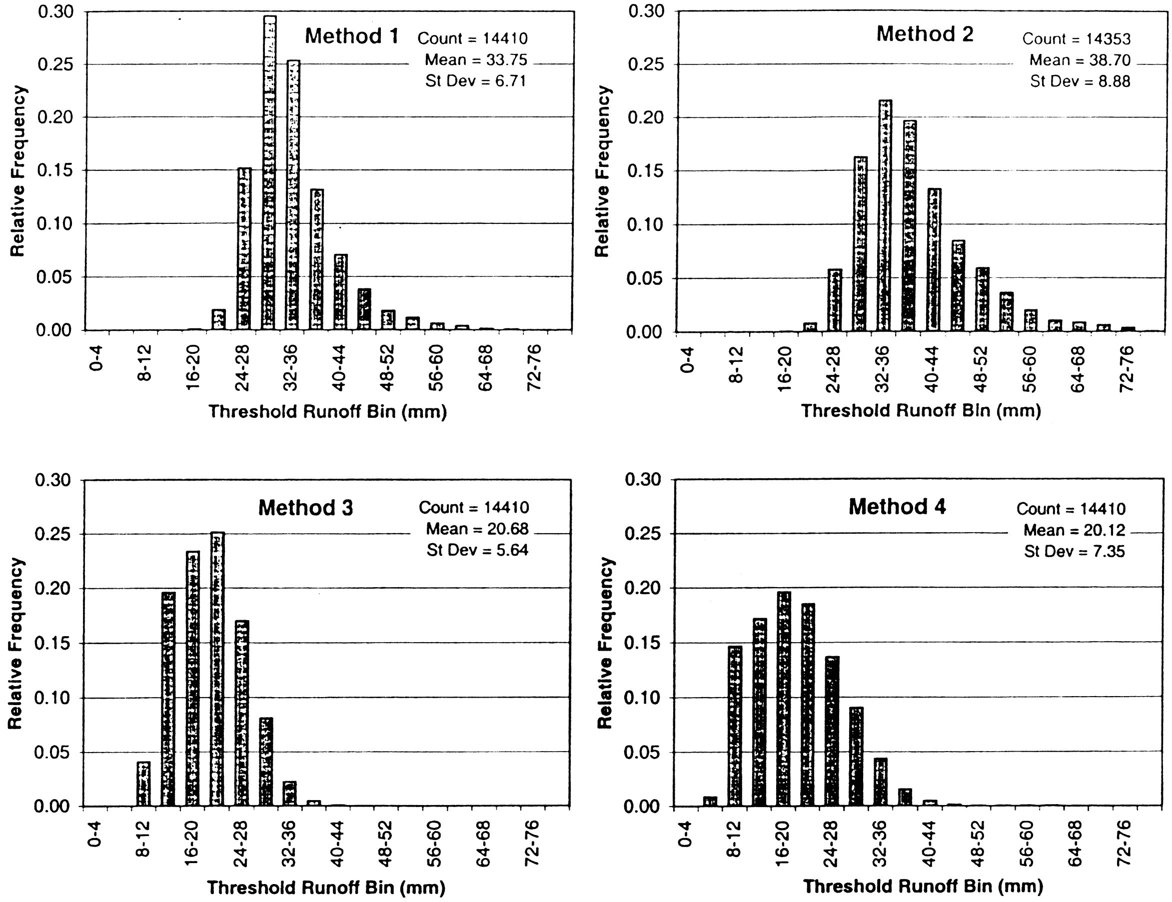


Fig. 8. Relative frequencies of threshold runoff for all four methods of computation in Oklahoma, effective rainfall duration is 1 h.

all Hydrologic Units processed. The effect of this assumed value was examined by determining watershed-specific R_L values, running the threshold runoff computations with the watershed-specific R_L, and, then, comparing these results with the threshold runoff values computed with the constant R_L. Only headwater Hydrologic Units, that is units containing the source of a river, were used. This included four Hydrologic Units in California, 13 in Iowa and 13 in Oklahoma.

R_L is defined as the average stream length of a given stream order divided by the average stream length of the next higher stream order. R_L was determined for each Hydrologic Unit as the best-fit slope from a plot of the logarithm of the average stream length against stream order. These values were, in general, slightly higher than the constant value of 1.9. The range in values was 1.9–2.8 in California, 2.0–2.9 in Iowa, and 1.8–2.6 in Oklahoma.

The comparison of threshold runoff values computed with the Hydrologic Unit-specific R_L versus the constant R_L is shown in Fig. 11. This plot shows Method 1 results with a 1 h effective rainfall duration for the three regions, and only for the source basins. Small sensitivity of the results on R_L is observed. Generally lower threshold runoff values were obtained with the Hydrologic-Unit-specific R_L, especially in Iowa and some regions of Oklahoma. The differences in threshold runoff values reach a maximum of 15–20%. Differences in the time to peak (not shown) were larger, up to about 30%.

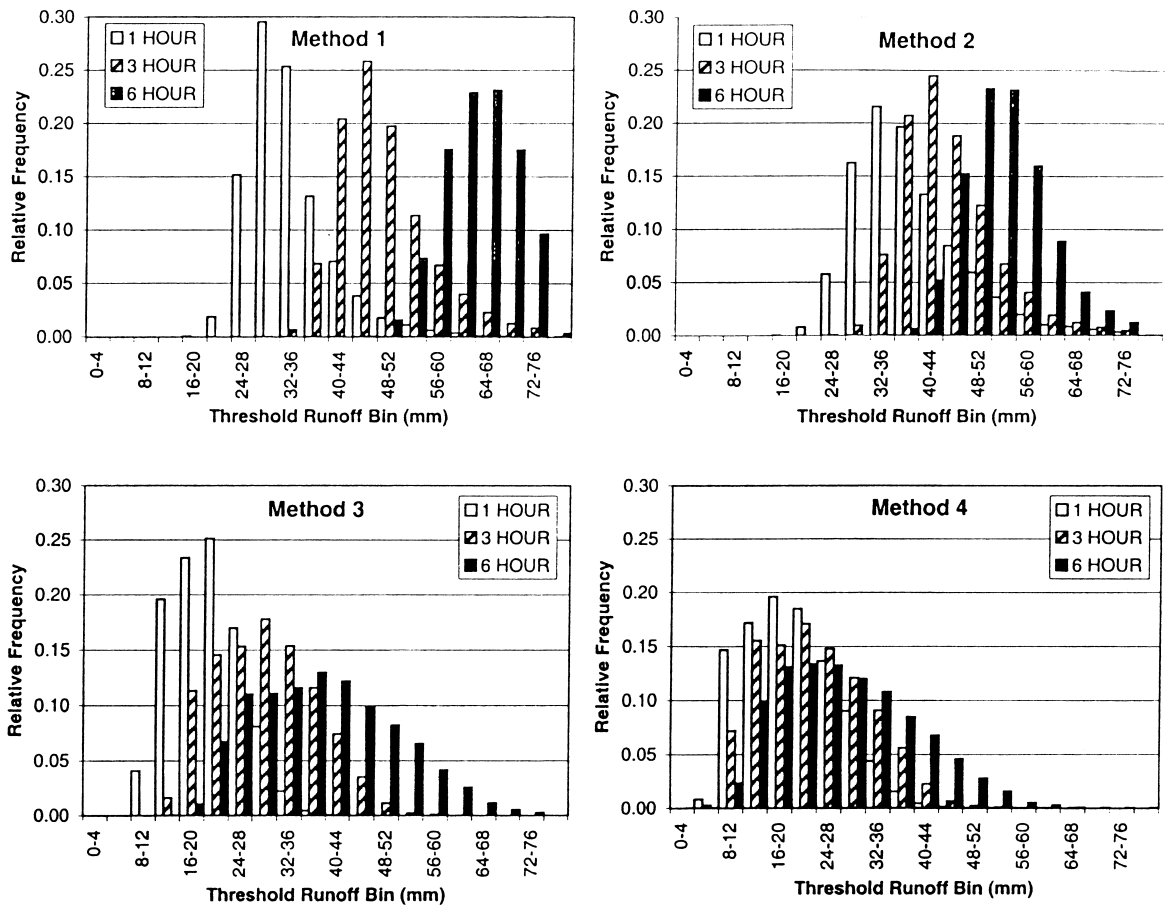


Fig. 9. Relative frequencies of threshold runoff for all four methods of computation in Oklahoma and effective rainfall durations of 1, 3, and 6 h.

4.3. Comparison with manually computed threshold runoff

In an effort to obtain a preliminary estimate of the accuracy of the procedure-computed threshold runoff estimates, their values were compared to values derived through manually computed methods. Observed precipitation and streamflow records were used to compute 1 h unit hydrograph peaks for selected streams in Iowa and Oklahoma. The unit hydrograph peaks were combined with estimates of the two-year return period and bankfull flows, and catchment area in accordance with Eq. (2).

For this work, only unregulated streams, with drainage areas less than 1500 km^2 were utilized. In total, 20 streams in Iowa and 16 streams in Oklahoma were used. The observed 15 min streamflow data at selected sites was obtained from the Iowa City, Iowa and Oklahoma City, Oklahoma offices of the USGS. Limited data was available, covering only the time period from January 1991 to December 1991 in Iowa, and from October 1991 to April 1994 in Oklahoma. With the available data, the first step was to identify possible rainfall–runoff events that could be used to develop unit hydrographs for the selected streams. Events were selected based on satisfying (or nearly satisfying) as many of the following criteria as possible: (1) uniform rainfall intensity in time, (2) isolated rainfall events, (3) single-peak discharge hydrographs, and (4) high peak discharge (near or greater than the two-year return period flow). In some cases, only one criterion may have been met.

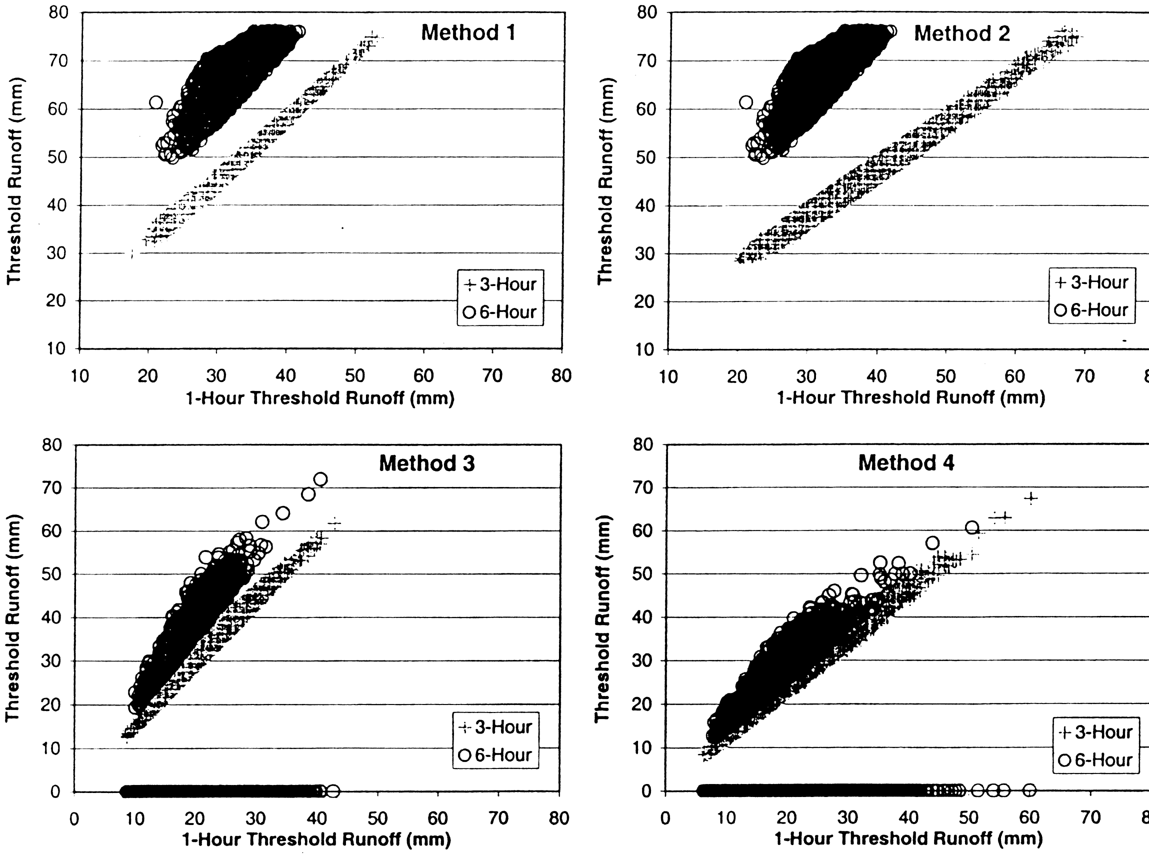


Fig. 10. Comparisons of 1-, 3-, and 6-h threshold runoff in Oklahoma.

However, in a few cases, multiple events for a given stream were identified and used in deriving the unit hydrograph.

For each stream and each event, a 1 h unit hydrograph was derived from the historical data. The derivation included separation of baseflow, direct runoff computation, and in some cases, transformation from the N-hour unit hydrograph to the 1 h unit hydrograph using an S-curve. Details of the unit hydrograph derivations are presented in Carpenter and Georgakakos (1993, 1995). The 1 h unit hydrograph peaks were obtained from the 1 h unit hydrographs, and combined with drainage area and estimates of the two-year return period or bankfull flows to arrive at the manually computed threshold runoff values.

Comparisons of the manually computed and procedure-computed threshold runoff for Iowa and Oklahoma are presented in Fig. 12. In this figure, manually computed threshold runoff is shown with filled symbols, and the procedure-computed values are given open symbols. Before discussing the results, we note the high uncertainty associated with deriving unit hydrograph estimates in basins with active subsurface runoff (as is the case for many basins in Iowa and Oklahoma). In Iowa, the manually computed threshold runoff shows greater variability than the procedure-computed values. The range in manually computed threshold runoff is 2–42 mm, whereas the range in procedure-computed values is 8–24 mm. Differences between the procedure- and manually computed values vary between 2 and 25 mm. These differences, if not a result of the uncertainties in the manual estimation of unit hydrographs for historical records, are a result of uncertainties in estimating channel cross-sectional properties. In Oklahoma, the procedure yields threshold runoff

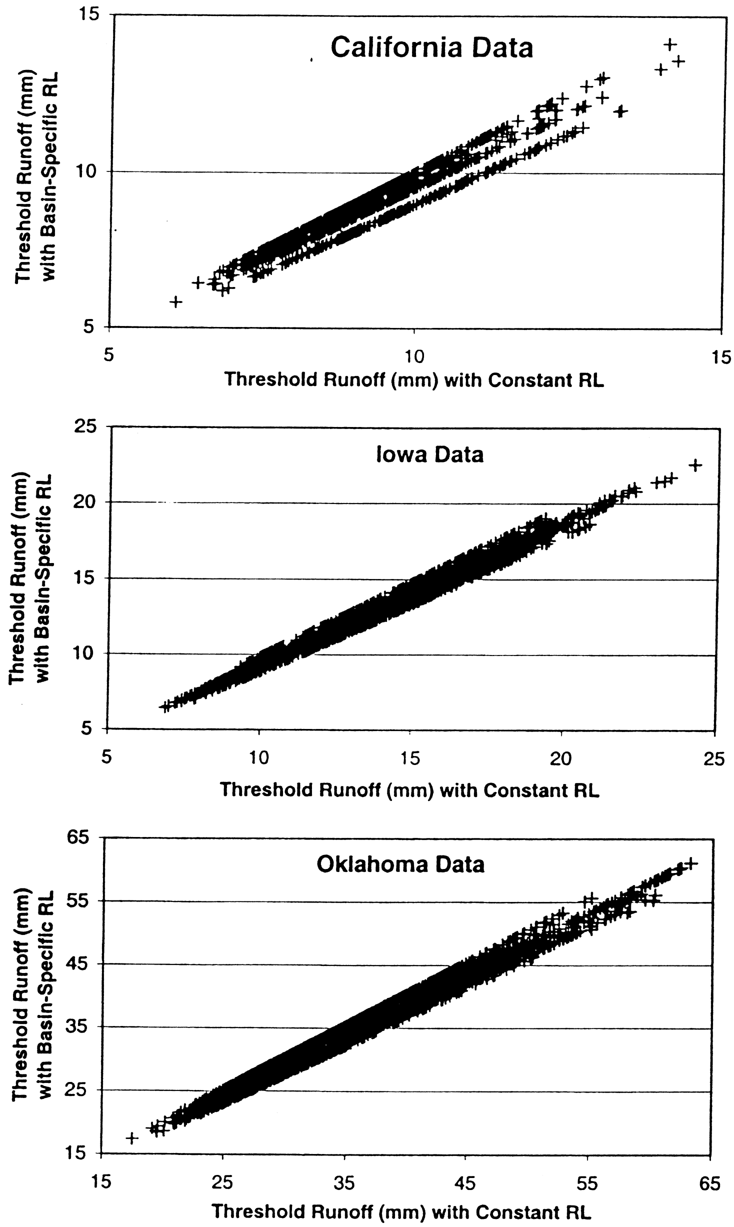
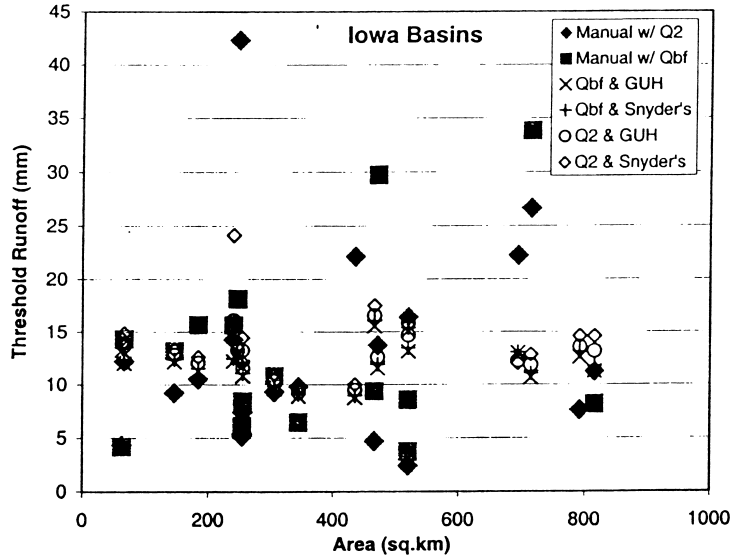


Fig. 11. Comparison of threshold runoff computed with a constant length ratio, R_L, over a region versus with a varying R_L. Method 1 is shown with a 1 h effective rainfall duration.

values with greater variability. The range in the procedure-computed values is 10–36 mm. The procedure-computed values are generally higher than the manually computed values. In Oklahoma, the differences range from 0 to 25 mm. It is noted that this maximum difference is obtained for the basin with the lowest drainage area. Excluding this basin, the maximum difference is approximately 15 mm. The mean square error between manually computed and procedure-computed values for Method 1 (Q_{bf}/GUH) was 8.9 mm in Iowa and 5.8 mm in Oklahoma. The two-year return period flow methods produced slightly



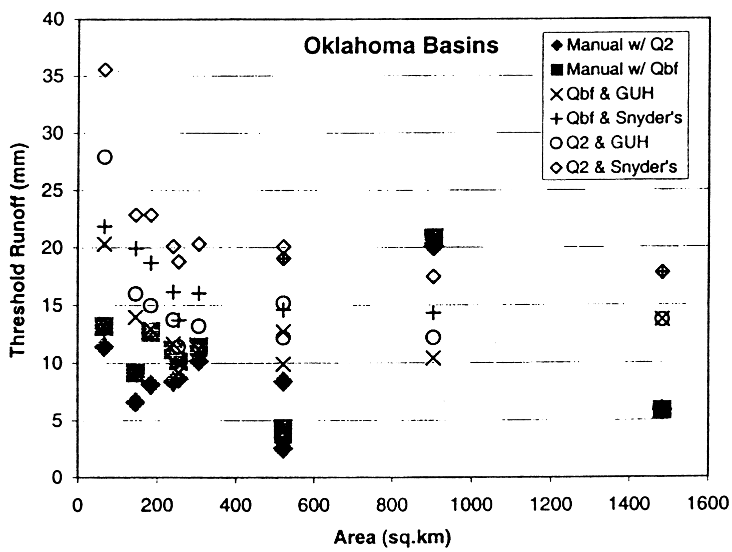


Fig. 12. Comparison of manually computed (filled symbols) versus procedure-computed (open symbols) hourly threshold runoff.

higher mean square errors than the bankfull flow methods (0.8–1.5 mm higher).

5. Summary, conclusions and recommendations

The US National Weather Service identified a need for improving flash flood guidance procedures. As a first step, this paper describes a procedure developed to provide improved estimates of threshold runoff. The procedure has been designed based on objective hydrologic principles and can be applied consistently on a national scale. It includes four methods of computing threshold runoff, to fit varying application needs and data availability scenarios for different regions within the US Geographic Information

Systems and nationally available digital databases are used in the determination of watershed geometric characteristics, needed to calculate threshold runoff. The procedure has been implemented in the software package, *threshR*, and is under operational implementation at regional River Forecast Centers.

The application of the procedure in three different regions has been demonstrated. These regions include the state of Iowa, the state of Oklahoma, and several areas in California. Analysis of the GIS-computed watershed characteristics showed significant similarities in the size of the delineated subbasins and subbasin stream length. The greatest difference in watershed characteristics was observed in channel slope. The average channel slope in California was nearly four times larger than in Iowa or Oklahoma.

Comparisons of the computed threshold runoff and computed unit hydrograph characteristics were made among the three regions, for the four methods of computations, and for varying effective rainfall duration. These comparisons showed substantially higher threshold runoff estimates in Oklahoma than in Iowa and California, with the values in Iowa being significantly higher than those in California. These differences are attributed mainly to differences in channel morphological properties (most likely a combination of terrain morphology and structure, and climate). For the method compared, Oklahoma had a mean threshold runoff value of nearly 34 mm. In Iowa, the mean value was 14 mm. California had the lowest mean value of 9.5 mm, along with the smallest range in values. A shift in the frequency distribution of threshold runoff for the methods using bankfull flow versus those using the two-year return period flow was observed in Oklahoma. This shift appears to be a function of the definition of the flooding flow, with bankfull flow producing higher threshold runoff than the two-year return period flow. Increasing the duration of effective rainfall produced higher threshold runoff values. For Oklahoma, a greater sensitivity to effective rainfall duration was observed with the geomorphologic unit hydrograph method than with Snyder's synthetic unit hydrograph method.

Perhaps one of the greatest sources of uncertainty comes from estimating channel cross-sectional and flow parameters from regional regression relationships. For some regions, these relationships may be established. If they are not, the relationships must be developed from local data within the region. This approach was used in Iowa and Oklahoma. The relationships developed have correlation coefficients ranging from 40 to 91%. The lower correlation coefficients (40%) affect the accuracy of the computed values (see theoretical sensitivity study reported in Carpenter and Georgakakos, 1993). Future developments should investigate the possibility of using high-resolution, remotely sensed data along with local surveys to estimate the channel cross-sectional geometry.

In the first implementation of the procedure in the NWS, there is an apparent advantage for using Snyder's unit hydrograph approach and the two-year return period flow (Method 4). There are problems in obtaining the necessary data to implement all methods. However, fewer problems are anticipated in obtaining the necessary data to implement Snyder's unit hydrograph (regional estimates of the empirical coefficients). Similarly, the two-year flow is available for streamgauge locations with fair national coverage. The cross-sectional data or regional relationships for cross-sectional parameters required to implement bankfull flow and geomorphologic unit hydrograph do not have the same availability on a national scale.

The final section of this paper presented a comparison of the procedure-computed threshold runoff values with values computed from manually determined unit hydrographs. Given the uncertainty associated with the manual procedure due to data variability, the comparison serves to obtain a preliminary estimate of the possible error in the procedure-computed values. Excluding one outlier of 25 mm for a small basin, a maximum difference in the threshold runoff values observed was 15 mm in both Iowa and Oklahoma. Of course, the ultimate validation of this procedure is in monitoring the results of real-time operation for providing flash flood guidance. Perhaps, newly available high-resolution remotely sensed data can be used to estimate excessive surface runoff areas for validation.

The next step is the implementation of the procedure in an NWS operational setting throughout the US Although the undertaking is large, it will generate a set of objective and consistent threshold runoff values across the US. Thus, it will provide excellent opportunities for understanding the spatial properties of threshold runoff, for estimating the reliability of the procedure, and for achieving further improvements in the methodology.

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